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ROBERT STUART SNYDER. The Optics of a Cosmic Ray Detection System Using a Gas Filled Cerenkov Detector. (Under the direction of E. D. PALMATIER and ROBERT MACE.) [redacted]

The use of a carbon dioxide gas Cerenkov radiation detector in a system to determine the charge distribution of the high energy component of the primary cosmic radiation is studied. The variation of the index of refraction of carbon dioxide with pressure was measured and this information used to select the velocity threshold of the particles to be detected. A Cerenkov detector containing carbon dioxide at 30 atmospheres pressure was operated successfully.

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THE OPTICS OF A COSMIC RAY DETECTION SYSTEM USING A GAS FILLED CERENKOV RADIATOR

by

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CHAPTER I

INTRODUCTION

A. Origin of this Study

The high energy component of the primary cosmic radiation consists mostly of atomic nuclei. The distribution of these primary charged particles with respect to atomic number Z is not well known because of the difficulties in obtaining data of good statistical accuracy outside the atmosphere.

Most of the information we now have about the abundance of the primary radiation has come from equipment carried aloft by balloons. The short duration of balloon flights, however, does not allow the collection of a large amount of data. The atmosphere still remaining above even the highest balloon altitudes (around 125,000 feet) is quite appreciable compared to the interaction length of the primaries and is sufficient to distort the Z distribution of the primary radiation.

As the primary nuclei penetrate the atmosphere, they interact with the various gas molecules. The nuclei lose energy by ionizing or exciting these molecules; or the nuclei can be fragmented upon colliding with other nuclei. This absorption of the primary radiation varies with the atomic number Z of the primary nucleus. For example, the probability of detecting heavy nuclei at sea level is completely negligible, whereas the probability that a primary proton, vertically incident upon the atmosphere, will penetrate to sea level is about 10^{-6}.

The advent of satellites gives us the opportunity to obtain this information above the atmosphere. The orbits of these satellites may be chosen sufficiently high in altitude above the earth that the atmospheric effect on the primary radiation is negligible. The duration of the satellite-borne experiments can be long enough to obtain the required information if the equipment can be kept operating. Thus the two disadvantages of balloon flights can be overcome by performing the experiment in a satellite. The equipment must be designed, however, to meet size, weight, and reliability requirements that restrict the methods that can be used to obtain the desired information.

For example, a magnet could be used to measure the curvature of the particles in a magnetic field. This method would not be feasible for a satellite-borne experiment because of the heavy magnets that would be required to obtain a suitable counting rate and measurable curvature of the tracks. There are devices which measure the ionization energy loss of the charged particles. Among these are:

1) Ionization chambers
2) Proportional counters
3) Low efficiency geiger tubes
4) Cloud chambers
5) Photographic emulsions
6) Scintillation crystals
7) Semiconductor detectors.

The first six items have been extensively used either in the laboratory or in balloon flights. Scintillation crystals and semiconductors are often considered for satellite equipment because of their small size and weight as well as their reliable and efficient operation. A method based on another principle is the Cerenkov radiation detector.

A study of a satellite-borne cosmic radiation detector to accurately determine the relative abundance of the various components of primary radiation is being conducted at the University of North Carolina. This study has shown that we may obtain the most satisfactory results from the use of the Z detection efficiency of scintillation crystals, semiconductors and Cerenkov detectors. Each device produces a light signal whose intensity is proportional to Z^2 for a constant particle velocity and particle path length through the medium. However, fluctuations in the Cerenkov light output from an operable Cerenkov detector prohibit Z discrimination with this method. This feature of the Cerenkov detector will be discussed later in Chapter II. Our study of Z discrimination was therefore restricted to the two ionization energy loss devices.

Examination of the process of ionization energy loss for particles of different Z traversing a scintillation crystal or semiconductor reveals that satisfactory Z discrimination is possible only if β, the velocity ratio of the particle, exceeds a certain minimum value. Figure I illustrates the dependence of the energy loss, dE/dx, for particles of different Z on the velocity β of the particle. The energy loss of the charged particle is proportional to Z^2 for a given β. As can be seen, a proton with $\beta \approx 0.33$ and an alpha particle with $\beta \approx 0.97$ have the same energy loss in the medium; and if one is attempting to determine Z by measuring the energy loss, these two particles can not be distinguished. The energy loss curves have a broad minimum at about $\beta \approx 0.97$; and for β greater than 0.97 the energy loss rate approaches a constant value known as the Fermi plateau. We see that we may obtain reliable charge resolution by restricting the particles we detect to those nuclei whose β is greater than 0.97.

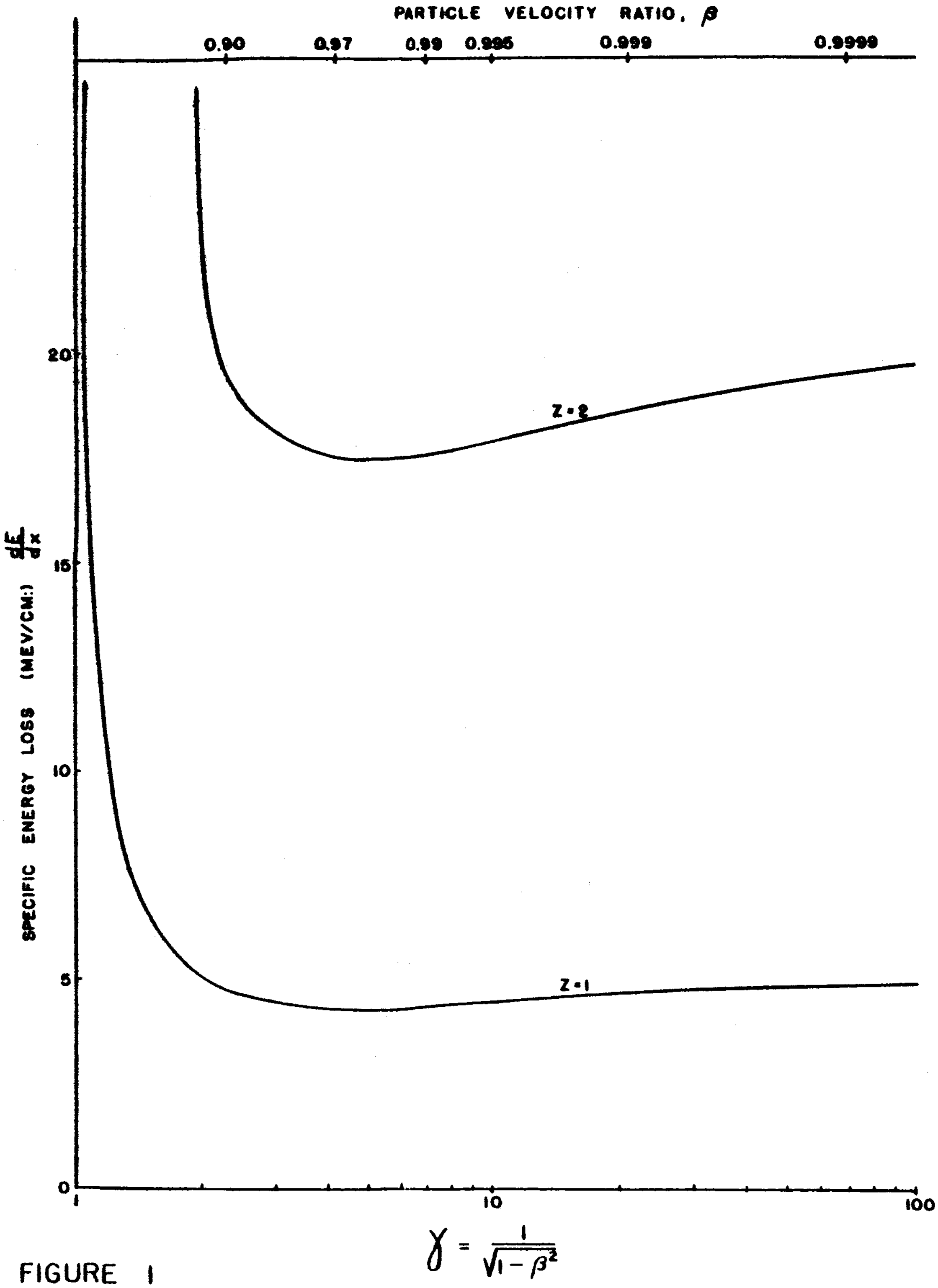


FIGURE 1

SPECIFIC ENERGY LOSS OF CHARGED PARTICLES IN NaI

We can achieve this selection of particle velocities by using a Cerenkov radiation detector. Cerenkov radiation is obtained when a charged particle traverses a transparent medium with a β greater than some minimum value. This feature of a threshold velocity for Cerenkov radiation will be discussed later in this thesis. By choice of the Cerenkov medium, we can select any value for the threshold, for example, $\beta = 0.97$.

The basis for our Z determination will then be to require that the primary cosmic nuclei produce a signal in both the dE/dx detector and the Cerenkov detector. Only if Cerenkov radiation is detected will we record and analyze the dE/dx signal, which is very closely proportional to Z^2.

Lau discussed the problem of Z discrimination for primary cosmic radiation in his Master's thesis.[12] He found that nuclei up to $Z = 12$ should be distinguishable using an NaI(Tl) scintillation crystal, provided a large number of particles are detected and provided the particles have $\beta > 0.97$. Semiconducting devices for Z discrimination are still in the development stage and not too much information is available on the type and size device which would be required. This thesis is not concerned with the final choice of the Z discriminator.

In this thesis we consider the problems relating to the use of Cerenkov radiation produced when a charged particle traverses a gas Cerenkov detector. We will find that only a gas medium will give us the β threshold of at least $\beta = 0.97$ which we require. In this discussion of the Cerenkov effect and the information that can be obtained from its use, we will also consider the advantages and disadvantages of using Cerenkov radiation to detect cosmic ray particles, related experiments that have been described in the literature, and recent designs that have been considered in this laboratory.

B. General Considerations of the Cerenkov Effect

Cerenkov radiation results when a charged particle traverses a transparent medium with a velocity greater than the local phase velocity of light. The electromagnetic radiation produced by the passage of the particle through the medium is strongly concentrated about an angle θ with respect to the direction of the particle, where, as indicated below, θ is a function of the particle velocity. Thus the ray paths of the Cerenkov radiation form right circular cones of half angle θ about the track of the particle. The wave front of the radiation produced by the particle is often compared to a hydrodynamic shock wave or to the surface bow wave produced in a fluid by a body moving with a speed greater than the wave propagation velocity of the fluid.

The "Cerenkov relation"[3] is:

1) $$\cos \theta = \frac{1}{\beta n}$$

where β is the ratio of the velocity of the particle to the velocity of light in a vacuum and n is the index of refraction of the transparent medium.

This equation predicts the minimum velocity ratio β of the particle that will produce Cerenkov radiation. If the β of the incoming particle is less than 1/n, the Cerenkov relation cannot be satisfied and the particle will not produce Cerenkov radiation. The index of refraction, n, of the medium thus provides a velocity threshold below which no radiation is produced. We need a transparent medium with an index of refraction of 1.031 to satisfy the Cerenkov relation for detecting primary cosmic particles above $\beta = 0.97$. Only a gas under pressure can have an index of refraction of this magnitude.

The energy of particles of known mass can be accurately determined by equation 1 if the angle θ can be measured. In an experiment proposed by Roberts,[17] where the possible particle paths are confined to narrow solid angles, it is possible to develop detectors based on the measurement of θ, in which β can be determined to an accuracy of 0.02% for an angular spread in the particle path of two milliradians. Unfortunately, in order to obtain a tolerable counting rate, any type of detector designed for use in a satellite-borne cosmic ray experiment must have a rather wide angle of acceptance. This not only eliminates the possibility of measurement of β but, as mentioned previously, it introduces severe fluctuations into the light collection efficiency of the Cerenkov system and renders it virtually worthless for the purpose of Z determination.

Frank and Tamm[7] developed the classical theory for Cerenkov radiation and obtained the fundamental equation for the energy W of radiation produced per unit path length

2) $$\frac{dW}{dx} = 4\pi^2 (Ze)^2 \int_{\lambda_2}^{\lambda_1} \left(1 - \frac{1}{\beta^2 n^2}\right) \frac{d\lambda}{\lambda^3}$$

where λ is the wavelength of the radiation and x is the path length of the particle of charge Ze in the medium.

The complication in the evaluation of this integral, which would arise from a strong dependence of n on λ, is avoided in our considerations by the restriction on the range of λ imposed by the transmission characteristics of the windows and the photomultiplier tube. As will be shown later, we are restricted to the wavelength interval from 3500 Å to 5800 Å. In this region, n for gases is usually a slowly varying function of λ.

This allows us to rewrite equation 2 as[15]

$$3) \qquad \frac{dW}{dx} = 4\pi^2 (Ze)^2 \left(1 - \frac{1}{\beta^2 n^2}\right) \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^3}$$

Now let the energy loss of the particle be represented by $Nh\bar{\nu}$ where N is the number of photons emitted in the wavelength interval from λ_1 to λ_2 and $h\bar{\nu}$ refers to the average energy of the emitted photons which we detect ($h\bar{\nu} = hc/\bar{\lambda}$). Since the wavelength interval from λ_1 to λ_2 is small, we can, to a good approximation, write $\bar{\lambda} = \frac{\lambda_1 + \lambda_2}{2}$; thus the integral in equation 3 can be expressed as

$$3a) \qquad \int_{\lambda_1}^{\lambda_2} \frac{d\lambda}{\lambda^3} = \frac{1}{\bar{\lambda}} \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

We may now rewrite equation 3 as

$$\frac{dW}{dx} = \frac{hc}{\bar{\lambda}} \frac{dN}{dx} = 4\pi^2 (Ze)^2 \left(1 - \frac{1}{\beta^2 n^2}\right) \frac{1}{\bar{\lambda}} \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

Since the path length through the medium is short enough that β is not reduced and noting that $\frac{e^2}{\hbar c} = 1/137$, we finally obtain

$$4) \qquad N = \frac{2\pi Z^2 x}{137} \left(1 - \frac{1}{\beta^2 n^2}\right)\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

An approximate relationship between the photon yield and the index of refraction of the gas is obtained by observing that both n for the gas and the β of the particle are close to one. By expressing $n - 1 = \varepsilon \ll 1$ and $1 - \beta = \delta \ll 1$ we find, to a first approximation,

$$\begin{aligned} 1 - \frac{1}{\beta^2 n^2} &= 2(\varepsilon - \delta) \\ &= 2\left[(n-1) - (1-\beta)\right] \end{aligned}$$

Equation 4 now becomes

$$5) \qquad N \approx \frac{4\pi Z^2 x}{137}\left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right)\left[(n-1)-(1-\beta)\right]$$

We note that β n approaches unity, $\left[(n - 1) - (1 - \beta)\right]$ and N approach zero.

All particles with a velocity greater than the threshold β will produce Cerenkov light. The variation of the photon yield with β above this threshold is one of the fluctuations in light output that prohibits our use of the Cerenkov detector as a Z discriminator.

It is important to note here the dependence of the amount of Cerenkov radiation on the index of refraction of the gas. Equation 1 showed how the index of refraction selects the Cerenkov threshold velocity β . The choice of the Cerenkov medium must be made with these points in mind.

C. Considerations Determining the Choice of the Cerenkov Radiator Material

Most of the experiments after World War II with Cerenkov detectors were centered around solid and liquid media, such as Lucite and distilled water, which have relatively high indices of refraction (1.49 and 1.33 respectively); and the resulting light yields were large enough for the newly developed photomultiplier to detect.

Initially gases could not be used because of their very low light yields and no effort was made to use gases at high pressures to increase the index of refraction and the light yield. As the photomultiplier tube was improved, gases such as air,[1] helium,[18] freon,[1] nitrogen[10] and carbon dioxide[8] came into use as Cerenkov media.

We chose carbon dioxide for our gas Cerenkov medium primarily because it is the most readily available transparent gas that would satisfy our index of refraction requirements at a moderate pressure. No reference could be found that carbon dioxide scintillates nor did we observe any scintillation during the experiment described in Chapter III. Carbon dioxide also has the desired properties of low Z to minimize multiple coulomb scattering of the particles and low density to minimize their energy loss and consequent velocity reduction while traversing the radiator.

The collection of the faint but highly directional Cerenkov pulses produced in gas at high pressure poses many problems. For the present study, the primary objective is the assurance that a charged particle, with velocity satisfying the Cerenkov relation and which is within the acceptance cone of the telescope, will produce a detectable signal.

This requires maximum efficiency for the production of the pulse and for its collection. In the following chapters, we will consider our two main problems, namely, the production and the collection of the Cerenkov light.

CHAPTER II

PRODUCTION OF PHOTONS

A. Direct Effect of the Primary Particle

We can obtain the photon yield for Cerenkov radiation produced in carbon dioxide from equation 5, the modified form of the Frank and Tamm equation,

$$N \approx \frac{4\pi Z^2 x}{137} \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)\left[(n-1) - (1-\beta)\right] \tag{5}$$

This equation allows one to determine the amount of radiation produced by each charged particle passing through the gas. We note that the radiation yield depends not only on the index of refraction of the medium and the velocity of the particle, but also on the square of the atomic number of the particle. This latter feature would be useful in determining the relative abundance of the primary cosmic radiation provided that the path lengths of the particles in the medium were constant, that the velocities were known and that the output of Cerenkov light was great enough, in each case, to reduce the effect of statistical fluctuations in the output pulses. As seen in equation 5, the light collection of the Cerenkov radiation detector depends strongly on both the particle path length and particle velocity β. The statistical fluctuations in the output pulse arise mainly from fluctuations in the light production and collection, even for constant β, and fluctuations in the photomultiplier response. The required resolution of the charge number is very difficult to achieve experimentally by the use of this Z^2 property since these requirements cannot be satisfied in a system which must conform to the space and weight restrictions under which we are operating and which is expected to be of large enough acceptance angle to produce a reasonable counting rate.

Since we cannot use the Z^2 dependence of the Cerenkov radiation yield because of the restrictions in the present design, equation 5 cannot be used by us to identify the primary particle. Our main concern is that all charged particles satisfying the velocity threshold requirement produce enough Cerenkov light to be detected by the photomultiplier. Examination of equation 5 does point out some ways that we can increase the amount of Cerenkov radiation that the photomultiplier will detect. These will now be examined.

The early experiments using gas Cerenkov detectors[9] compensated for low photon yields by long particle path lengths in the medium. Due to the size limitation imposed in the present study, this method cannot be used to increase our Cerenkov light output.

The wavelength limits shown in equation 5 are determined by the transmission of the window and the response of the photomultiplier. The Cerenkov radiation spectrum is continuous and if we can widen the spectral response of the photomultiplier, we will detect more of the Cerenkov photons. Quartz has better transmission in the ultraviolet than glass and its use allows us to increase the wavelength limit in the ultraviolet. This is the important region for us since, according to the Frank and Tamm equation, the number of photons produced per wavelength interval is proportional to $1/\lambda^2$.

It is important now to clarify the status of an often used device insofar as it affects our experiment. The $1/\lambda^2$ dependence led some experimenters to use wavelength shifters to increase the amount of light transmitted by the window and detected, in its operating region, by the photomultiplier. Wavelength shifters are intended to absorb the copious ultraviolet part of the Cerenkov radiation and reemit in the usable visible and near ultraviolet. Many investigators have reported an increase in the number of usable photons of 100% or more. Recently, however, it has been shown that the increased light has been due to scintillation caused by the ionizing particles penetrating the medium. This, of course, would destroy the threshold feature of the Cerenkov detector. Hence, wavelength shifters are of no value in this experiment.

By changing the pressure of the gas within reasonable limits, the index of refraction and therefore the threshold β may be controlled. Carbon dioxide, a gas of average index of refraction at atmospheric pressure, has a high critical pressure and therefore a considerable increase in n over its value at atmospheric pressure is possible. Since the index of refraction will be used primarily to set the velocity threshold of the Cerenkov detector, this method cannot be used to increase the light yield.

There is insufficient published information on the index of refraction of gases suitable for Cerenkov media at high pressure. Jennings and Kalmus[10] built an interferometer into a nitrogen Cerenkov detector to find the index of refraction at operating pressure. Perez-Mendez and Atkinson[15] also measured the index of refraction versus pressure for their Cerenkov media, SF_6 and $CClF_2$.

At the beginning of our study of the Cerenkov detector, we were unable to locate published information on the variation of the index of refraction of carbon dioxide with pressure. Jelley[9] examined the case where $n - 1 \ll 1$ in the Lorentz-Lorenz formula which leads to $n - 1$ proportional to the density. (The Lorentz-Lorenz formula is discussed in the Appendix.) He then made the perfect gas assumption and obtained n - 1 proportional to the pressure. This approximation is acknowledged to hold only at "moderate pressures."[8] Hanson and Moore, however, applied this relationship to carbon dioxide at 63.5 atmospheres and predicted a maximum index of refraction for the gas as 1.026. As noted in Chapter I, we need an index of refraction of 1.031 to detect particles with β greater than 0.97. Figure II is a graph of the index of refraction of carbon dioxide and the threshold particle velocity β versus the carbon dioxide pressure. The dashed line shows the results of Hanson and Moore.

If the Beattie-Bridgeman Equation,[2]

$$p = \frac{RT(1-\varepsilon)}{v^2}(v+B) - \frac{A}{v^2}$$

is used to find the pressure-density relationship rather than Boyle's Law, the Lorentz-Lorenz formula predicts an index of refraction of 1.05 at 63.5 atmospheres. This result is of great importance from the safety and weight viewpoint as it would allow us to operate the satellite-borne Cerenkov detector at a lower pressure. An experiment using a Michelson interferometer and a small gas pressure cell was performed to examine the discrepancy. Our experimental index of refraction versus pressure curve is shown as a solid line in Figure II. This measurement and a more detailed examination of the results and the theory are discussed in the Appendix.

Cerenkov radiation is emitted instantaneously as the charged particle traverses the medium. The duration of the light pulse at the window is a function of the dispersion of the medium, the variation in lengths of optical paths to the light detector and the time of traversal of the particle. For systems with less than a 75 centimeter particle path

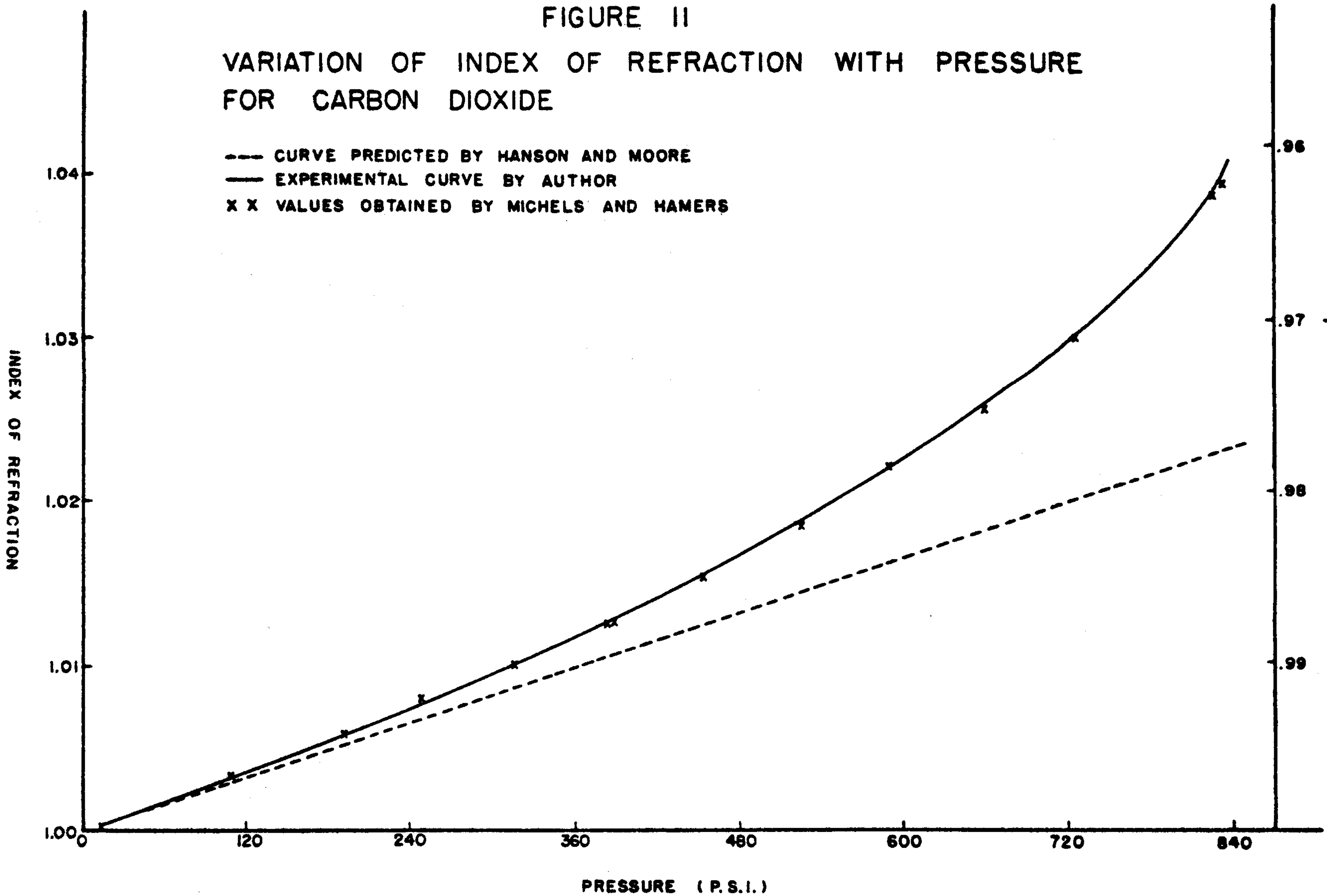


FIGURE II

VARIATION OF INDEX OF REFRACTION WITH PRESSURE FOR CARBON DIOXIDE length in the medium, similar to our detecting system shown in Figure III, the contribution to the pulse width due to these considerations is less than one nanosecond.

B. Spurious Effects

Spurious effects accompanying the production of Cerenkov radiation must be estimated or measured. We must be sure that the light pulse seen by the photomultiplier is due only to the Cerenkov radiation generated in the carbon dioxide by single heavy charged particles.

Atomic or molecular radiation caused by ionization or excitation can be produced by particles traversing the detector with a velocity below the Cerenkov threshold. This scintillation occurs within a time of about one nanosecond,[5] which is comparable to a fast Cerenkov pulse and would be difficult to distinguish.

The particle may be part of a cosmic ray shower consisting mainly of high energy electrons. If these electrons have a velocity above the Cerenkov threshold, the Cerenkov radiation produced could be incorrectly recorded as due to a heavy particle having a velocity above the Cerenkov threshold. A shower detecting shield of geiger tubes, which can be arranged around the Cerenkov radiation system, reduces this possibility.

A heavy charged particle may be traversing the gas below the Cerenkov threshold velocity, but it may give sufficient velocity to an ionization electron which then produces Cerenkov light. The light from this "knock-on" electron must be discounted if the results of the experiment are to be valid. Events due to knock on electrons produced in the gas and container walls cannot be distinguished from a Cerenkov pulse. S. P. Viswanathan[19] has studied knock-on electrons in metals and found an expression for the probability that an incoming particle of energy E gives rise to a secondary knock-on of energy E′. His results may be readily used to ascertain the probability of spurious events arising from wall generated secondaries.

Neither Parnell's experiment nor the experiment reported in this thesis was able to detect these effects with any confidence. Chapter IV contains a discussion of the conclusions reached concerning spurious radiation.

CHAPTER III

COLLECTION OF PHOTONS

The Cerenkov radiation generated in a gas filled Cerenkov detector is small in magnitude but highly directional relative to the paths of the particle which generate it. Our main problem is to efficiently collect this radiation. Since the gas is contained under pressure and a photomultiplier tube is required to detect the small amount of Cerenkov light produced, provision must be made to get the Cerenkov radiation out of the tank.

The transparent window through which the Cerenkov radiation is transmitted to the photomultiplier must not lie in the path of the charged particles. Transparent solids have an index of refraction much higher than gases and therefore, according to the Cerenkov relation, the velocity threshold for the production of Cerenkov radiation will be much less than the $\beta = 0.97$ we desire.

Placing the window, and also the photomultiplier tube because of its glass envelope, out of the path of the particle creates a problem for the collection of the Cerenkov photons. This radiation will have to be reflected by the interior of the gas container toward the window and photomultiplier tube. There are various geometrical arrangements that have been investigated to find the best method for reflecting and collecting the Cerenkov light. This chapter will consider the more important experimental designs we have used.

A. Experiment Number 1

The feasibility of using a carbon dioxide Cerenkov detector at pressures ranging from 15 to 30 atmospheres was investigated by T. A. Parnell and is discussed in his Master's thesis.[14] He performed a sea level experiment using hard mu-meson secondaries to generate the radiation. The gas was contained in a cylindrical steel tank with a lucite window at one end. A geiger tube telescope restricted the detection of the mu-mesons to those lying within a small solid angle. The axis of the tank was tilted relative to the axis of the telescope so that the window would not be traversed by the accepted particles.

The interior of the steel tank was polished and this surface used to reflect the Cerenkov photons toward the photomultiplier. In spite of the fact that polished steel is a poor reflector of visible and near ultraviolet and that the rays were reflected at a large angle of incidence, a sufficiently high output of Cerenkov light was obtained to justify further investigation of this method.

B. Experiment Number 2

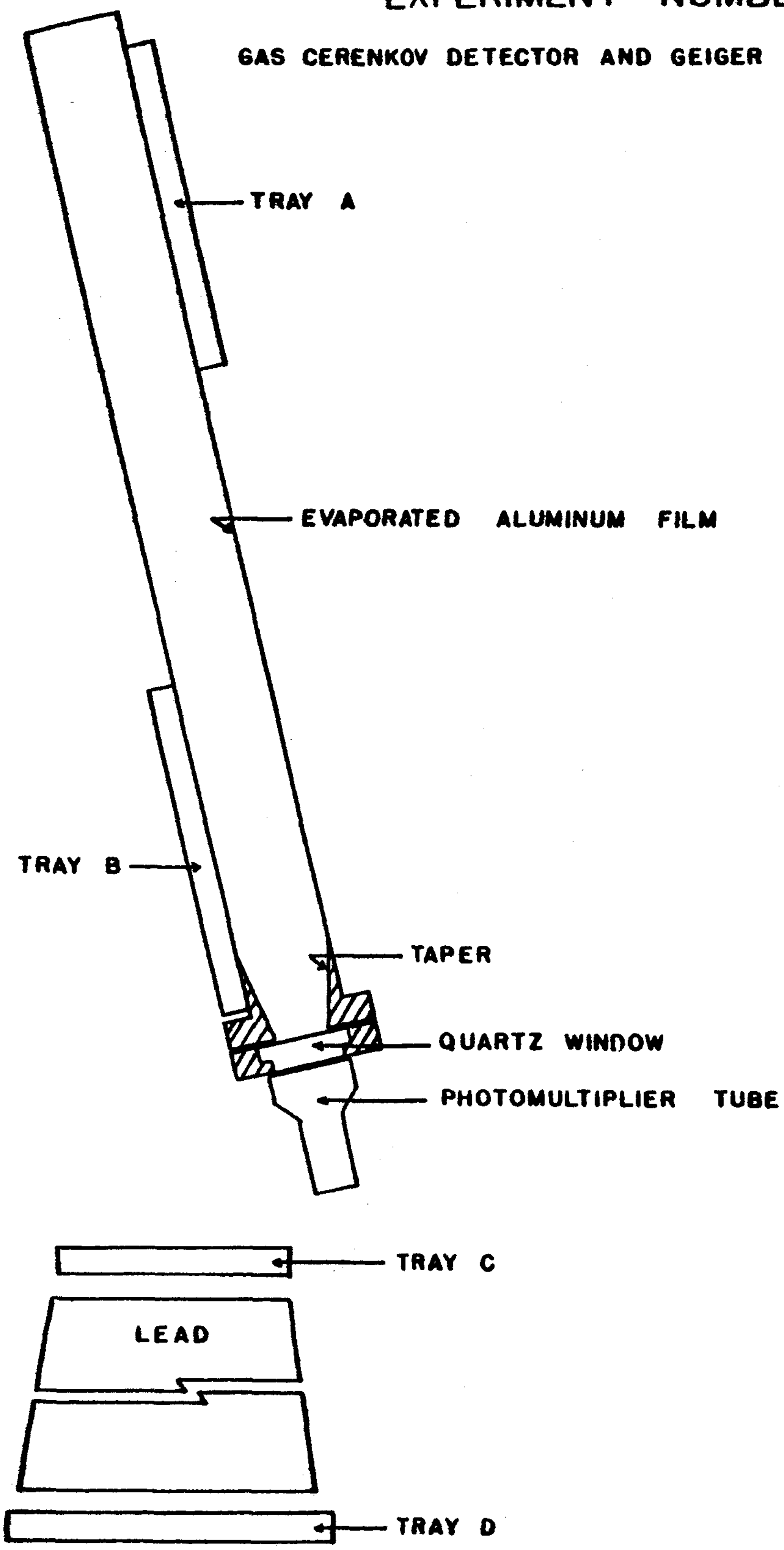
A second experiment was undertaken to improve on the detection system used by Parnell. The experimental arrangement is shown in Figure III.

Instead of using the reflection from polished steel, the interior of the tank was lined with a sheet of opaque Mylar to which an evaporated aluminum film had been applied by Evaporated Metal Films, Inc. Although the evaporated aluminum film is virtually opaque to visual light, we used opaque Mylar as a backing instead of a transparent solid to further reduce the possibility of unwanted Cerenkov radiation getting into the tank. An evaporated aluminum surface, the best specular reflector known to us, reflects up to 90% of the incident light at normal incidence in

FIGURE III

EXPERIMENT NUMBER 2

GAS CERENKOV DETECTOR AND GEIGER TUBE TELESCOPE



the near ultraviolet and visible.

A quartz window was used on the tank instead of lucite to transmit the Cerenkov radiation because of its transmission and strength properties. We were not able to get a suitable quartz window photomultiplier and so the transmission advantage of the quartz tank window was not utilized.

A final objective of this experiment was to check out the associated electronic circuitry, particularly some transistorized printed circuits that would be used in a satellite experiment. These circuits functioned satisfactorily.

The basic layout of the equipment does not differ radically from Parnell's thesis experiment. The cylindrical steel tank is tilted at an angle of 12° from the vertical to place both the quartz window and the photomultiplier tube outside the path of the particles.

A stainless steel tank of one-eighth inch wall thickness was used to contain the carbon dioxide. This thickness provides an adequate safety factor at the pressures used but does not significantly slow down the high energy particles being examined. The path of the particle through the tank was defined by a geiger tube telescope consisting of geiger tube trays A, B and C. Trays A and B each contained two geiger tubes for the telescope and two independently operated geiger tubes, one on each side, to detect showers. Events in coincidence with a shower signal were recorded separately and these are shown in columns 4, 5, 6 and 7 in Table I.

Since the sea level component of cosmic radiation contains a soft component consisting primarily of electrons and slow mu-mesons, all of which may trigger the telescope but not be of sufficient velocity to produce Cerenkov radiation, a lead absorber and an additional geiger tube tray D were added. The lead absorbs the electrons and soft mu-mesons but not the more energetic "hard" component, consisting almost entirely of fast mu-mesons. A mu-meson having sufficient range to penetrate the lead absorber and be detected by the D tray should produce Cerenkov radiation in the tank.

The dimensions of the interior of the tank were decided as the result of an extended ray tracing study. Ray tracing allows us to follow, in principle, the path of the Cerenkov photon as it is reflected in the tank. Although Cerenkov photons may be emitted at any point of the particle's path in the medium and therefore we are dealing with the production of photons from an extended source, each photon is emitted at a definite angle with respect to the path of the particle. If we know the path of the particle, we can choose various points on this path as the source of Cerenkov photons, draw the paths of these photons, and determine whether the photon will reach the photomultiplier and the number of reflections the photon must undergo. Several representative particle paths were treated in this fashion.

Using this ray tracing procedure, it was found that the cross-sectional area of the inside of the tank must not differ greatly from the photocathode area of the photomultiplier. The inside diameter of the tank is 3 inches and a taper was required near the end of the tank to condense the light toward the 2.5 inch diameter photocathode. Ray tracing showed that approximately 3 per cent of the rays are back reflected within this taper.

It is seen by referring to Figure III that the minimum path length is about one-fourth of the average path length and the maximum exceeds the average by about 20%. The minimum path length is approximately 15 centimeters. The Cerenkov photons produced by a particle taking this minimum path through the gas undergo a maximum of three reflections before reaching the window. This situation is the worst possible case for both the production and the collection of the Cerenkov light. If the tank contains carbon dioxide at 30 atmospheres, equation 5 shows that, on the average, 230 photons are generated by the mu-meson traversing this minimum length and one expects about 85% of these photons to reach the window.

A clear fused quartz window was chosen to contain the carbon dioxide in the tank and transmit the Cerenkov radiation to the photomultiplier. Quartz has higher strength and better transmission in the near ultraviolet than Herculite, the only other satisfactory material available at the time. Although most of the Cerenkov photons are reflected by the aluminized walls of the tank, transmission through the interface of the carbon dioxide and the quartz is not as efficient. The amount of light transmitted at the junction of two media is a function of the angle of incidence and the difference between the indices of refraction. Considering these factors, probably about 45 per cent of the Cerenkov radiation is transmitted by the quartz to the photomultiplier.

The quartz was cut in the form of a top hat and all surfaces were polished. A steel flange was bolted to the bottom of the cylindrical tank, pressing the quartz into contact with an O ring to form a pressure seal. The photomultiplier was then placed in direct contact with the lower, smaller surface of the quartz window. Dow Corning Silicon Fluid 200 was used to provide an optical coupling between the quartz and photomultiplier.

A compromise had to be made in the choice of photomultiplier. A large area photocathode decreases the amount of conical taper needed inside the tank but the larger tubes have a larger dark current. The low light output we expect from the carbon dioxide requires maximum sensitivity and quantum efficiency for this photocathode as well as a minimum dark current and maximum signal to noise ratio. Unfortunately all of these requirements are not compatible. New tubes have been developed with dark current of about 12 electrons/cm.^{2}/sec., but this improvement also reduces the quantum efficiency from 10% to about 7% and the response from 50 μA/lumen to 30 μA/lumen. The smaller dark current allows the detection of weaker signals, however, and this improvement is sufficient to justify the decreased output pulse height.

The tube chosen for the experiment was the E. M. I. 9578S that has a 2.5 inch photocathode diameter and an S-11 response. The photocathode has a peak quantum efficiency of 7% at 4400 Å falling off to about 1% efficiency at 3500 Å and 5800 Å. The efficiency spectrum can be extended into the ultraviolet by using a quartz window on the photomultiplier and it is hoped that this feature can be added in the future.

Considering the result obtained above of 230 photons generated in the Cerenkov detector by a single charged particle traversing the minimum path length in the gas, we can expect a minimum of about 90 photons to reach the photocathode of the photomultiplier. For an average photocathode efficiency of 4%, about 4 photoelectrons are produced by the photocathode. This number should provide a detectable pulse for our measuring apparatus.

Chapter IV contains a discussion of the results of this experiment. Although we found that all singly charged particles produced enough Cerenkov radiation in the gas to be detected, several of the features of this experiment need more careful examination. It is highly desirable to eliminate the large particle path length variation in the gas. A stronger material for the tank window is needed. To use quartz at a safety factor of seven to one, we would need a window thickness exceeding one inch. The heavy flange arrangement required to attach the quartz window to the tank accounts for a large part of the weight allotted to us for a satellite-borne experiment.

It is hoped to solve the window problem by using a new, high strength glass, Chemcor, now being developed by the Corning Glass Company. Samples have been received at this laboratory for testing. One of these samples, 3.5 inches in diameter and 0.155 inches thick supported a pressure of 900 pounds per square inch before rupturing.

C. Experiment Number 3

A third design for a gas Cerenkov detector is presently under investigation. The axis of the cylindrical tank is not tilted relative to the axis of the telescope as in the previous experiments; and the window is attached at the side of the tank. A single curved mirror at the bottom of the tank reflects the Cerenkov light toward the side window and photomultiplier tube.

The primary disadvantage of this design is the massive flange required to support the window against the side of the tank and stiffen the cylinder around the window. The weight limitation for satellite-borne experiments may not allow the use of this design. It should be possible, however, to use this design in a series of balloon flights.

The advantages of this design include the following: 1) The path length variation of the particles traversing the tank will be less than in any of the previous experiments. It does not appear that this decrease is yet sufficient to allow us to use the Cerenkov detector as a Z discriminating device but it will be interesting to compare the Cerenkov light output with that of the scintillation crystal or semiconductor.

2) There is a possibility of more efficient light collection due to the reduction in the angles between the axis of the tank and the directions of the accepted particles.

CHAPTER IV

DISCUSSION OF EXPERIMENT NUMBER 2

Table I summarizes the experimental results obtained from various pressure runs with the gas Cerenkov detector shown in Figure III. It was hoped to operate part of the time at the maximum pressure of 60 atmospheres; but at around 50 atmospheres the quartz window ruptured, causing the destruction of other equipment. This quartz window had been designed with a safety factor of 4 to 1 for a pressure of 60 atmospheres and had been previously tested at this pressure for an extended time. Although it is believed that the rupture was probably due to an improper seating of the quartz window, it was decided to run all subsequent tests with a second quartz window at 30 atmospheres or lower since we could not be certain of our diagnosis without an extensive test program for quartz windows.

Geiger tube tray D was designed with an area sufficient to detect all of the high energy mu-mesons when the tank pressure was 50 atmospheres or higher. At these high pressures we could have accurately determined the efficiency of the entire Cerenkov detector. The area of the D tray unfortunately covered only 91% of the incoming flux for the 30 atmosphere run. It was therefore expected that 9% of the Cerenkov pulses would occur without triggering the D tray.

When our pictures of all events were examined, it was observed that almost half of the Cerenkov pulses were caused by particles that did not trigger the D tray. To determine the source of this error, an evaluation of the expected particle density and energy distribution was carried

TABLE I DATA FROM EXPERIMENT NUMBER 2

No. of run	Characteristic of run	Pressure (atm.)	Index of Refraction	$\beta_c = \frac{1}{n}$	Momentum P_c $\left(\frac{Mev}{c}\right)$	Range in Pb corres. to P_c $(gm.\ cm.^{-2})$	Thickness of Pb used $(gm.\ cm.^{-2})$	% D tray coverage	Total No. of Events (ABC)
1	normal position	30	1.015	.985	626	575	562	91	450
2	inverted position	30	1.015	.985	626	575	562	91	345
3	normal position	30	1.015	.985	626	575	562	91	149
4	inverted position	30	1.015	.985	626	575	562	91	592
5	normal position	30	1.015	.985	626	575	562	91	526
6	normal position	15	1.007	.993	957	870	894	84	451

TABLE I DATA FROM EXPERIMENT NUMBER 2 (continued)

No. of run	Pressure (atm.)	Total No. of Events (ABC)	$ABC\bar{D}S$ no pulse	$ABC\bar{D}S$ with pulse	ABCDS no pulse	ABCDS with pulse	Total Excluding Showers $ABC\bar{S}$	$ABC\bar{D}$ no pulse	$ABC\bar{D}$ with pulse	ABCD no pulse	ABCD with pulse
1	30	450	15	77	3	27	328	105	109	1	113
2	30	345	39	37	14	18	237	138	1	97	1
3	30	149	7	18	1	3	120	18	42	0	60
4	30	592	61	38	22	16	455	243	3	204	3
5	30	526	12	70	1	27	416	76	128	1	211
6	15	451	14	67	1	23	346	84	144	0	118

out. The counting rate for the penetrating particles agreed with the many previous experiments done in the laboratory. Approximately 70% of all of the incident particles are hard mu-mesons that should have penetrated the lead and the D tray. The ratio of all of the Cerenkov pulse events to the total number of incident particles was very close to 70%. The D tray therefore should have detected many more of the particles than it did.

A check of the electronic circuitry showed that it was operating correctly. The geiger tubes were checked periodically and a couple of them had varying plateau voltages. The malfunction of one or more geiger tubes during the course of the experiment would have given us the above results, and it is quite probable that this was the cause of the trouble.

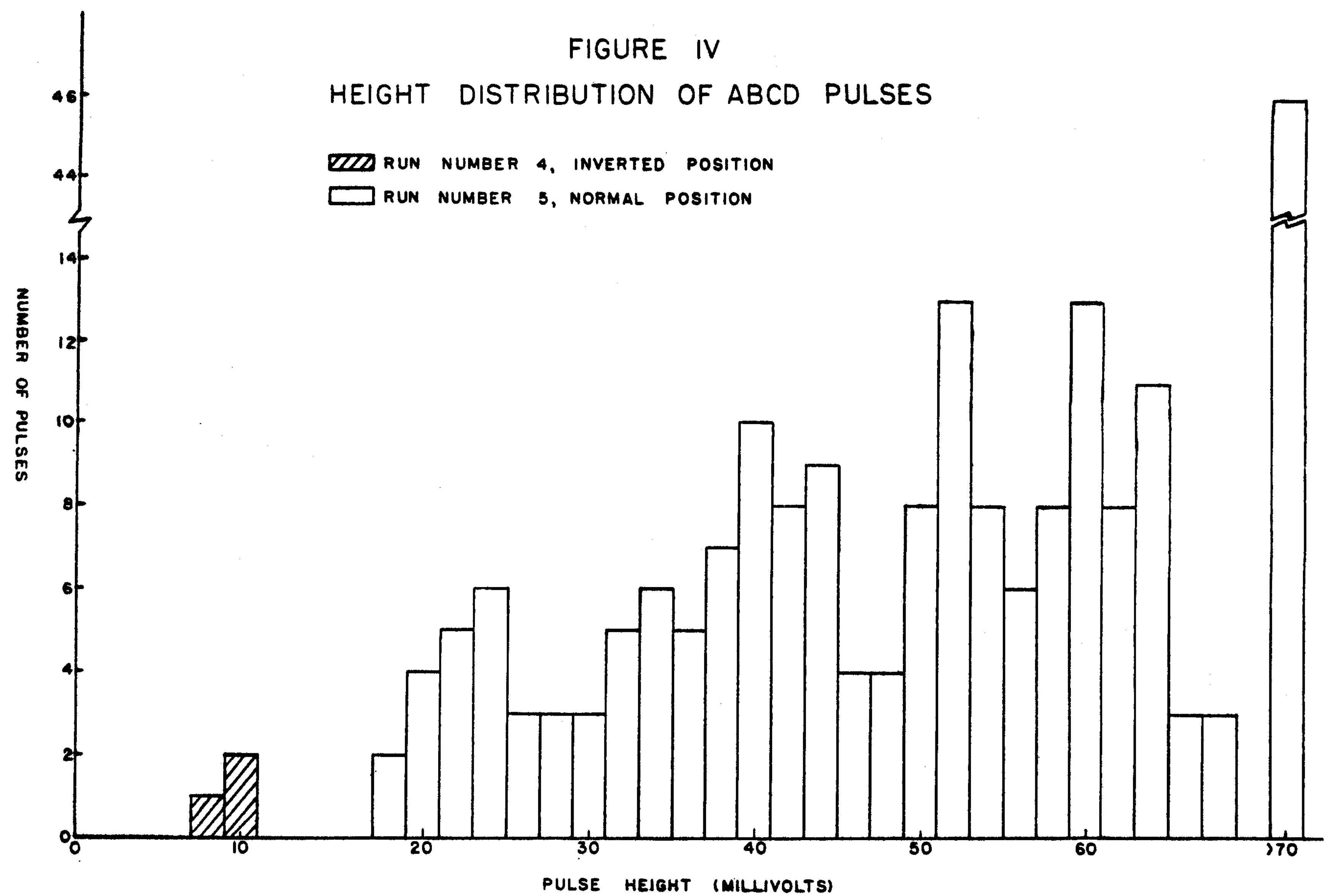
The effect of this difficulty was the rejection of much data. Most of our objectives were realized, however, and are discussed in the following pages.

The Cerenkov detector was primarily operated at 30 atmospheres and an evaluation of these runs is outlined below. Pulse height distribution curves, with the detector in both the normal and the inverted position, are given in Figure IV.

384 out of 386 high energy mu-mesons that triggered the D tray gave detectable and usable signals. The passage of two of the mu-mesons gave no detectable pulse. This is readily attributable to shower events which we did not detect or to those particles with velocity only slightly above the Cerenkov threshold so that their output of Cerenkov light is too low to detect. This latter effect could have been due to the low production of Cerenkov light by particles with velocity just above the Cerenkov threshold, leading to an effective Cerenkov threshold

FIGURE IV

HEIGHT DISTRIBUTION OF ABCD PULSES



slightly above that predicted by equation 1. Furthermore, a similar number of the "good" events may be due to showers.

The Cerenkov tank was inverted to investigate the presence of scintillation light or any other spurious light producing effects occuring when the mu-mesons traverse the tank. Since the inside of the tank at the end opposite the photomultiplier was covered with black felt which would not reflect the Cerenkov light back toward the photomultiplier, the possibility of Cerenkov radiation being reflected up into the photomultiplier was negligible. Four small pulses were observed during the time that 301 high energy mu-mesons went through the inverted system and triggered the D tray. This number is somewhat less than our estimate of such spurious events which was based on extensive calculations pertaining to knock-on secondaries generated at the top of the tank or in the gas and showers which were not completely excluded.

The largest of these spurious pulses was one half the size of the smallest Cerenkov pulse obtained with the tank in its normal position. The mode of the two pulse height distributions differed by more than a factor of ten. If one attributes these signals to scintillation light, (which is not necessary in view of the fact that they can be accounted for entirely by other means) then the most energetic output observed of the isotropic scintillation (per centimeter of path length) as the particle traverses the entire length of the tank, is less than 10% of the least energetic output of Cerenkov light (per centimeter of path length) and less than 2% of the average Cerenkov light output (per centimeter of path length). This amount of scintillation light is within the tolerable limits for effective operation of the instrument.

CHAPTER V

CONCLUSION

From our study of a Cerenkov radiation detector containing carbon dioxide at 30 atmospheres, designed with regard to a particular set of restrictions on weight, size and geometry, we conclude that:

1) All charged particles passing through the system with a velocity greater than the effective Cerenkov threshold velocity yield detectable and usable Cerenkov signals. This is the primary purpose of our Cerenkov detector.

2) Scintillation is negligible compared to Cerenkov radiation using carbon dioxide as the Cerenkov medium. These two results justify further development of the gas Cerenkov detector for a satellite-borne experiment.

The measurement of the variation of the index of refraction of carbon dioxide with pressure agrees very well with the theory, when proper consideration is given to the behavior of the gas density as a function of pressure. This is of importance to our project since we conclude that the output of Cerenkov photons at a pressure of 30 atmospheres is about 20% greater than one might conclude by extrapolating to higher pressure the results cited by Jelley.

APPENDIX

A literature study of the properties of carbon dioxide was undertaken initially to find whether the gas at high pressure would scintillate or fluoresce when subjected to high energy particles or the passage of the Cerenkov electromagnetic pulse. As noted in Chapter II, measurements of the index of refraction were performed when a literature survey revealed inconclusive results.

The experimental arrangement for the index of refraction measurement consisted of a Michelson interferometer and sodium discharge lamp to produce the fringe pattern. A stainless steel pressure cell with one half inch quartz windows, containing gas at various pressures, was inserted into one of the optical arms of the interferometer. As the gas was leaked into the cell from a high pressure source, the number of fringes that were displaced could be counted. The high pressure source was a cylinder of commercial grade carbon dioxide at a pressure of about 830 p.s.i. A pressure control valve and ballast tank were used to produce slow pressure changes in the system. The optical path through the gas in the cell was 0.250 inches. A Bourdon type pressure gauge with an accuracy of $\pm$ 5 p.s.i. was used for pressure measurements.

The pressure system was flushed many times with carbon dioxide to eliminate the air and any other impurities and the experiment was begun with the gas at a pressure of one atmosphere in the cell. The pressure was increased slowly so that about two fringes passed the cross-hairs of a telescope each second. Each step of the experiment involved visually counting about fifty fringes with the aid of the telescope. A manual counter was used to record this number of fringes. At the end of each run, about one minute was allowed to assure temperature equilibrium. Usually a change of one or two fringes occurred in this interval while the system attained equilibrium, requiring an adjustment in the recorded fringe shift.

The entire procedure was repeated until the maximum tank pressure was reached. Then the pressure was slowly released and the same fringe counting procedure continued until the pressure was down to one atmosphere. Four complete runs were made in addition to four partial runs in the high pressure range where the deviations from the perfect gas law would occur.

The change of index of refraction in each step is related to the number of fringes passing across the field of view of the observer by the following relation:

$$\Delta n = \frac{\lambda}{2t} \Delta N$$

where t is the geometrical path in the pressure cell of the sodium light of wavelength λ and ΔN is the number of fringes counted as the pressure changed. Since the index of refraction of carbon dioxide at atmospheric pressure is well known, the index of refraction at any other pressure can be found by measuring the fringe shift.

A theoretical check of the experimental curve is obtained from the Lorentz-Lorenz formula,

$$\alpha_e = \frac{3}{4\pi N} \frac{n^2-1}{n^2+2}$$

which expresses the electronic polarizability, α_e, as a function of the index of refraction of the gas, n. N is the number of molecules present per unit volume and can be expressed as $\frac{N_o \rho}{W}$ where N_o is Avogadro's number, is the density of the gas and W is its molecular weight. An alternate form of the Lorentz-Lorenz equation defines the molar refractivity, M, as

$$M = \frac{4\pi}{3} N_0 \alpha_e = \frac{W}{\rho} \frac{n^2-1}{n^2+2}$$

The following experimental reports were found in the literature as the above work was being performed. Phillips[16] used a Fabry-Perot etalon to trace the pressure dependence of M through both the gas and liquid phases. Coffin and Bennett[4] used similar apparatus and found that the molar refractivity did not vary for most of their pressure runs up to 30 atmospheres. They did obtain a variation when the carbon dioxide was taken from steel storage containers over 5 years old. They credited the large decrease in M to the presence of the polar molecule carbon monoxide, which seems an incorrect conclusion. Landolt and Bornstein[11] have an excellent summary of the theory and a list of the experimental results for most of the gases. One of their references for carbon dioxide is the paper by Michels and Hamers[13] in which the same experiment on the variation of index of refraction with pressure was reported. For pressures up to 63 atmospheres, their results, shown in Figure II, agree very closely with the experimental results obtained with the Michelson interferometer and show no significant variation of M. The average molar refractivity of carbon dioxide obtained from our experiment is 7.1 cm.^{3} per mole and the average found by Michels and Hamers is 6.69 cm.^{3} per mole.

If the molar refractivity of carbon dioxide is a constant, it can be shown that $\frac{\Delta n}{\Delta \rho}$ is also a constant as long as the approximation $n^2 - 1 \ll 1$ holds. As a final check on our results, $\frac{\Delta n}{\Delta \rho}$ is plotted as a function of density ρ in Figure V. Even though our curve shows

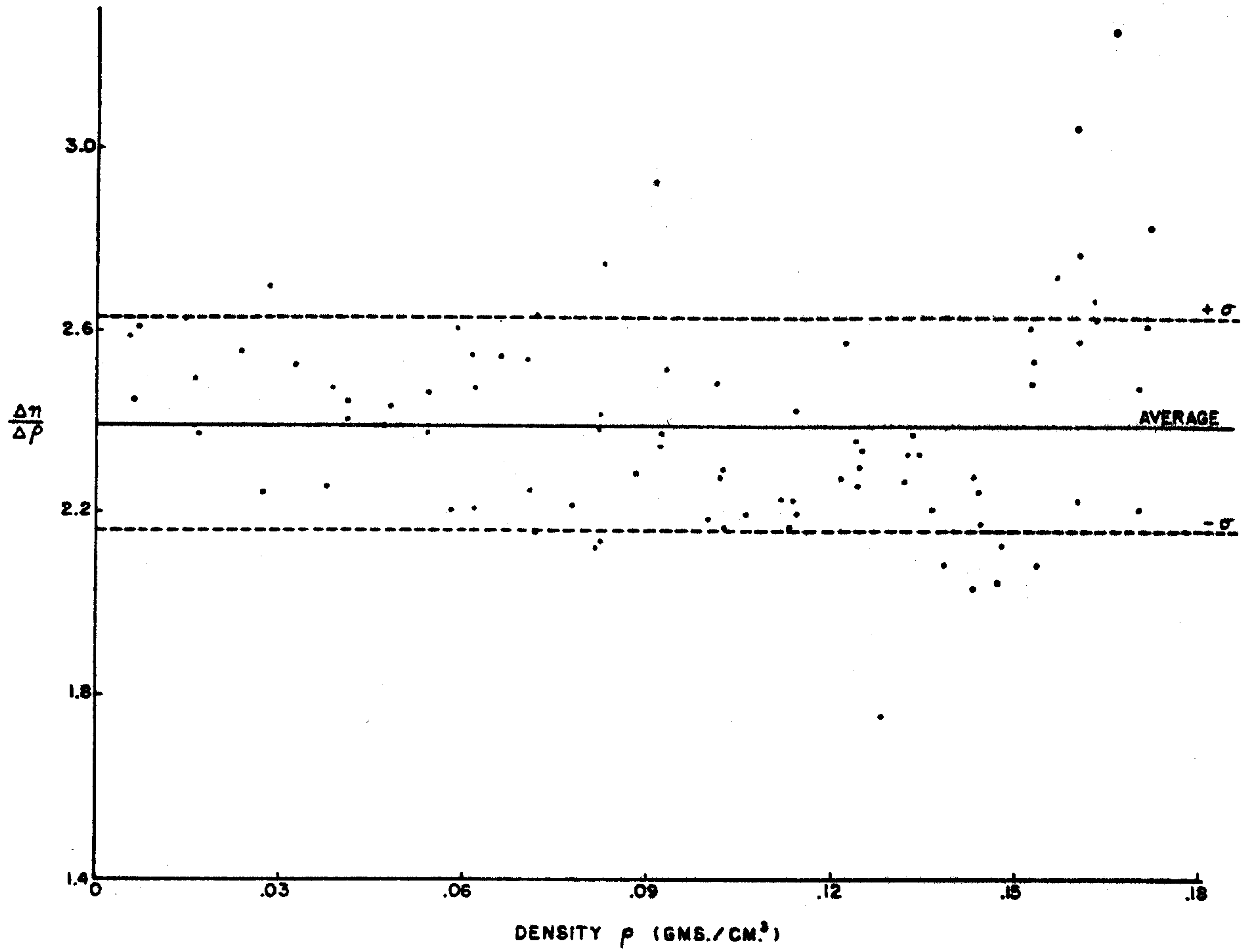


FIGURE V DEPENDENCE OF INDEX OF REFRACTION ON DENSITY FOR CARBON DIOXIDE a fluctuating slope, 69% of the points lie within one standard deviation of the average value of $\frac{\Delta n}{\Delta \rho}$ in spite of the apparent changing slope and large spread of readings for each density range.

The importance of knowing the variation in the index of refraction of carbon dioxide with pressure has been stressed in the previous chapters. The results that we have obtained in this study agree quite well with the theory and with the very extensive and thorough work of Michels and Hamers.

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